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TROPICAL CYCLONE DAMAGES IN CHINA UNDER GLOBAL WARMING

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Abstract: Over the past 25 years, an annual average of 6 to 7 tropical cyclones (TCs) made landfall on China mainland and Hainan Island with an average intensity of 29.9 m/s at landfall and maintained at least tropical storm intensity for 15.6 hours over land, leading to 505 deaths and 37 billion yuan in direct economic loss, which accounted for 0.4% of the annual GDP of China. Although there was little change in the overall landfall frequency, intensity at landfall and overland duration, the annual total direct economic loss increased significantly due to the rapid economic development over the past 25 years. Under global warming, the intensity of TCs that made landfall on Hainan decreased but the overland duration and frequency of TCs that made landfall on Fujian and Zhejiang increased. At the national and provincial levels, the ratio of the direct economic loss to GDP and casualties caused by landfall tropical cyclones decreased, suggesting the effectiveness of disaster prevention and reduction in China.

Key words: tropical cyclone; track; economic loss; global warming

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1 INTRODUCTION

Tropical cyclones (hereafter TCs) are usually accompanied with strong winds, torrential rains[1], high waves, and storm surges, which cause severe disasters. TC-related disasters are one of the worst natural disasters in China, causing great loss of life and property. All levels of the Chinese governments have paid great attention to TC-related disaster prevention and reduction. The Ministry of Civil Affairs of China and the China Meteorological Administration have systematically collected, verified and compiled the TC-related disaster information since 1983, which has been released by the State Statistics Bureau of China in recent years. Although studies have been conducted on TC-related disaster[2-4], two important scientific issues associated with them still remain, i.e., the effectiveness of TC-related disaster prevention and reduction, and the impact of global warming on TC-related disasters in China. This study attempts to discuss these scientific issues through an analysis of the data over the past 25 years so as to provide a scientific basis for the prevention and reduction of TC-related disasters in China.

Recently, Zhang et al.[2] analyzed the characteristics of TC-related disasters during 1983–2006. They found that the annual total economic loss directly caused by TCs has shown a significant upward tendency since 1983, due to the rapid economic development in China in the past 30 years. Although there is little change in the overall TC-related disasters, the regional trends should not be overlooked. For example, Zhang et al.[2] noted that although an annual average of three TCs make landfall on Guangdong province, the direct economic losses and casualties in Zhejiang province, which receives an annual average of one landfall TC, are a few times as many as those in Guangdong. Therefore, possible shifts in the TC prevailing tracks under the background of global warming[5-9] might have an important impact on disaster prevention and reduction in China.

Researches in the past decades showed that the

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activity of western North Pacific (WNP) TCs affecting China experienced significant changes[5-9]. Webster et al.[5] and Emanuel[6] pointed out that under the background of global warming the power dissipation index (PDI) over the past 35 years has increased markedly and the intense TCs (maximum wind speeds larger than 58.6 m/s) have increased significantly. Recently, Wu et al.[7, 8] reported that the changes in the TC prevailing tracks and formation locations may have contributed to these increases. Wu et al.[9] argued that the changes of TC prevailing tracks enhance the TC influence along the southeast coast (Fujian and Zhejiang), but decreased it over South China (Hainan and Guangdong). Yang et al.[10] found that the frequency of TCs that made landfall on South China is also reduced. Tu et al.[11] also found that TC tracks over WNP-East Asian region shift from the South China Sea and the Philippine Sea to the vicinity of Taiwan Island and the East China Sea since 2000. Gong et al.[12] documented that the subtropical high strengthens and spreads southwestward significantly after 1980, leading to relatively less TC activity in the regions south of 20°N. Zhou et al.[13] found that the westward extension of the subtropical high is mainly caused by both the cooling in the central and eastern tropical Pacific and the increased convective heating in the equatorial Indian Ocean.

Meteorologists have made every effort to understand TC-related disasters. Chen et al.[3] related TC strong wind, precipitation, landfall intensity (defined as the TC intensity at landfall) and moving speed to TC-related damage and established a statistical prediction model for TC-related disasters. Li et al.[4] used an analytical hierarchy approach to assess TC-related disasters. Pielke et al.[14, 15] argued that changes in inflation, wealth and population should be taken into account in the study of disaster losses. Additionally, the research on statistical characteristics of TC landfall provided useful information for the study of TC-related disasters[16-18]. However, these studies did not consider the impacts of the changes in TC activity on TC-related disasters in the past several decades.

Previous studies on TC-related disasters in China mainly focus on the natural factors, such as TC intensity, frequency and duration, but less attention has been paid to social factors such as economic development, population densities and wealth increase. In order to identify the effectiveness of disaster prevention and the impact of global climate change on TC-related disasters in China, this study will consider not only the natural factors, but also the social factors including economic development, population growth and changes in consumer prices.

Data used in this study are introduced in section 2. Section 3 describes the variation of TC-related damages in China and the changes of the overall landfalll TC frequency, intensity and overland duration. In section 4, we discuss the TC-related disasters of coastal provinces and the corresponding frequency, intensity and duration of landfall TCs. Concluding remarks are given in section 5.

2 DATA AND METHODOLOGY

The TC best track datasets from Shanghai Typhoon Institute, China Meteorological Administration (STI-CMA) and Joint Typhoon Warming Center (JTWC) are used in this study. They include TC position (latitude and longitude) and intensity at 6-hour intervals. Note that although the STI-CMA dataset has more observational information in China, the JTWC dataset will also be analyzed as reference. The TC-related damage data from 1984 to 2008 are available from the Department of Civil Affairs of China (no data for the regions of Hong Kong, Macau, and Taiwan), including the direct economic losses and deaths caused by TCs. Recently, the National Climate Center of CMA reanalyzed the damage data. In order to make the economic losses comparable in different years, the data of direct economic losses are adjusted to the same currency scale based on Gross Domestic Product (GDP) deflator in the study of Zhang et al.[2]. In this study, the Consumer Price Index (CPI) is used for better reflecting the price changes. In recent years, CPI has been gradually become a hot topic in China and its changes have greatly influenced nearly all aspects of everyday life. The data of GDP and population are downloaded from the State Statistics Bureau of China (www.stats.gov.cn), while the CPI data are taken from the website "Measuring Worth" (www.measuringworth.com).

3 TC-RELATED DAMAGES IN CHINA

3.1 *Total damages*

The CPI data are utilized to adjust the direct economic losses caused by TCs at the 2008 currency level. Figure 1 shows the time series of the economic losses directly caused by TCs, both unadjusted and adjusted, for 1984–2008. The annual direct economic losses before and after the adjustment are 28.9 and 37 billion yuan (equivalent to US$4.2 billion and US$5.4 billion based on the exchange rate on 31 December, 2008), respectively. The adjusted losses are much larger than 28.7 billion yuan (US$4.2 billion) in Zhang et al.[2] because they used the GDP deflator to adjust the TC-related direct economic losses, which differ little from the unadjusted results in this study. With the rapid development of the Chinese economy, the CPI is an important factor for measuring TC-related damages. Especially in 2008[19], the CPI had an accumulative increase of 6.3% from January to

November.

Both the unadjusted and adjusted losses have increased substantially at the 95% confidence level (The trend significance in this article is tested with the Mann-Kendall method[20]). As shown in Figure 1, extraordinary TC-related losses occurred in 1994, 1996, 2005, 2006 and 2008, which were associated with extreme TC events, such as Fred in 1994, Herb in 1996, Matsa in 2005, Bilis in 2006, and Hagupit in 2008.

Since the 1980s, China has experienced rapid economic development. As a result, damages caused by TCs have increased due to the economic development. For this reason, the GDP (Figure 2) and the GDP per capita (figure not shown) are used to adjust the direct economic losses. Both of them show similar changes since the population has grown linearly and slowly in the last 30 years. The direct economic losses (see Figure 2) are not adjusted by CPI owing to the unadjusted GDP. The annual direct economic losses by TCs account for 0.4% of the total GDP in China, which is very close to the 0.38% suggested in Zhang et al.[2], indicating that the difference of TC-related losses between this study and Zhang et al. mainly result from the currency adjustment. Figure 2 indicates that the TC-related direct economic losses scaled with GDP have a decreasing trend that is opposite to the absolute economic losses, although the decreasing trend is not statistically significant. It can be inferred that the growth of annual direct loss (as shown in Figure 1) is due to the economic development, which is in agreement with Zhang et al.[2].

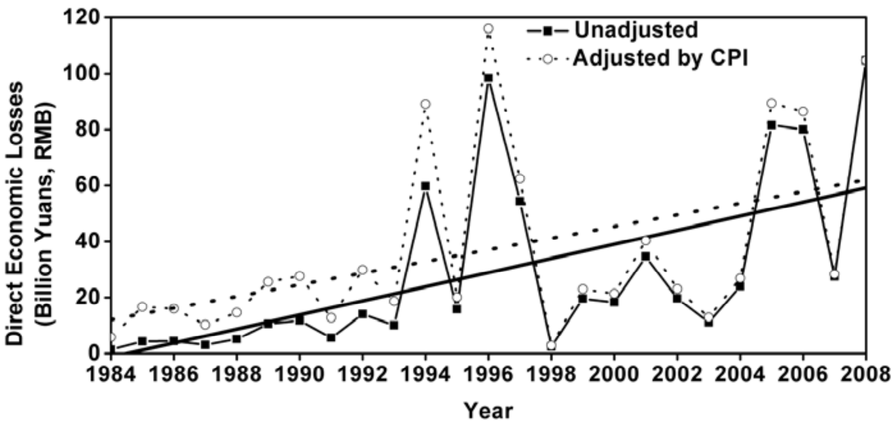

Figure 1. Direct economic losses due to landfall TCs (thin curve, unit: billion yuan) and the corresponding linear trend (thick curve), which pass the 95% confidence level.

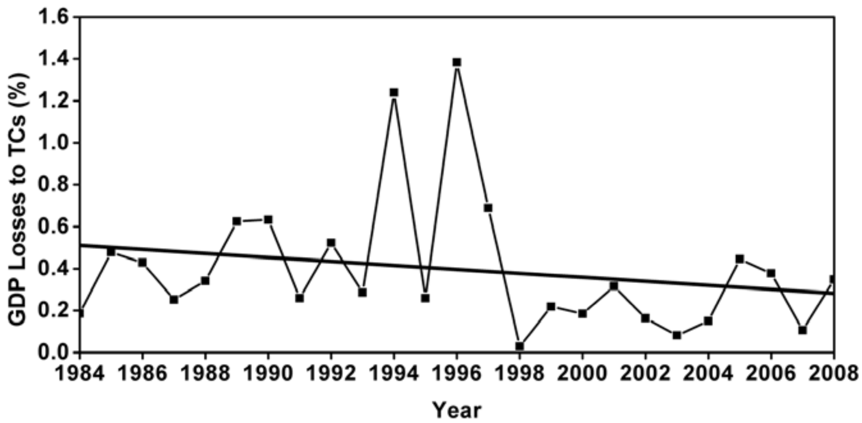

Figure 2. Direct economic losses due to landfall TCs relative to the annual Chinese GDP (thin curve, unit: %) and the corresponding linear trend line (thick curve), which do not pass the 95% confidence level.

It is well known that there is uncertainty in direct economic loss data because they are estimated by all levels of governments. Meanwhile, the casualties are more reliable because counting the number of fatalities is much easier than estimating the economic losses. Figure 3 shows the number of the annual deaths caused by TCs is 505, which has a significant decreasing tendency at the 95% confidence level. Taking the accuracy into account, we can argue that the downward death trend is consistent with that in the normalized economic losses, suggesting that the direct economic loss data can be used to estimate the trend of TC-related disasters.

3.2 *Changes of landfall TC frequency, intensity and overland duration*

TC-related disasters are closely related to the characteristics of TC activity including landfall frequency, intensity and overland duration. In other words, these parameters are applied to indicate trends in TC activity rather than to explain TC-related disasters. Figure 4 shows the TC landfall frequency in the STI-CMA dataset during 1984–2008 and in JTWC dataset from 1984 to 2007. There are 162 and 140 TCs making landfall on China mainland and Hainan Island according to the STI-CMA dataset and JTWC dataset, respectively. In Figure 4, although TC landfall frequencies are slightly different, the two datasets show obvious interannual variations. The JTWC dataset indicates a slightly downward trend. The number of annual landfall TC is 6.5 (5.8) in the STI-CMA (JTWC) dataset, which is less than that (8 TCs) found in the study of Li et al.[17] because of their inclusion of tropical depressions. In the period of 1984–2007, the STI-CMA dataset indicates more landfall TCs in 11 years while the JTWC suggests more landfall TCs in 5 years. Figure 4 suggests that the total number of landfall TCs from the STI-CMA dataset is more than that from the JTWC dataset. The STI-CMA dataset indicates more TCs making landfall on China mainland and Hainan Island during 1985–1989 and less landfall TCs from 1990 to 1998. The TC frequency making landfall is closely consistent with the frequency of TC occurrences in Ren et al.[21]. They found that the TC information in the STI-CMA data before 1990 was a combination from several departments, while the JTWC data after 1989, especially during 1993–2003, show a trend toward a larger number of and more intense TCs. As shown in Figure 4, the STI-CMA dataset recorded more TCs making landfall since 2000 on mainland China and Hainan Island than the JTWC dataset, though with similar interannual variations.

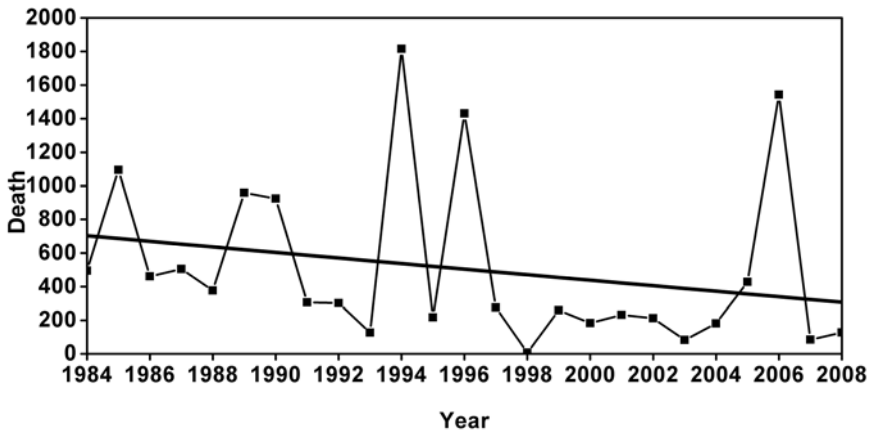

Figure 3. TC-related casualties in China from 1984 to 2008 (thin curve) and the corresponding linear trend line (thick curve), which pass the 95% confidence level.

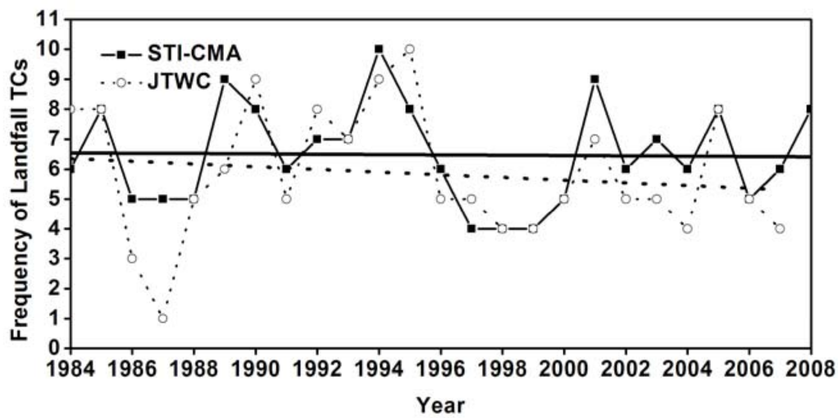

Figure 4. Annual frequency of TCs making landfall based on the STI-CMA dataset from 1984-2008 and the JTWC dataset from 1984-2007 (thin curve) and the corresponding linear trend lines (thick curve), none of which passes the 95% confidence level.

Landfall intensity is an important factor for TC-related disasters. It is noted that caution should be taken to analyze the TC intensity because different time periods are used for averaging in the two datasets. In the JTWC dataset, the maximum wind speed is averaged over one minute while being averaged over two minutes in the STI-CMA dataset. Figure 5 gives the time series of landfall intensity in the STI-CMA dataset during 1984–2008 and that of JTWC during 1984–2007. On average the landfall intensity is 29.9

m/s (31.2 m/s) in the STI-CMA dataset (JTWC dataset). It has a slow upward trend over the past 24 years according to the JTWC dataset while showing little change in the STI-CMA dataset, with interannual variations in both datasets.

Annual total overland durations of TCs from the STI-CMA dataset during 1984–2008 and the JTWC during 1984–2007 are plotted in Figure 6. The total overland duration for a year is described as the time between the landfalling and the weakening of a TC into a tropical depression or moving into the sea. [Overland duration of TCs is calculated as follows: The sum of trajectory points is added up for TCs that are over land with intensity at or above the level of tropical storm (17.2 m/s) and then multiplied with 6 (hour)]. If a TC makes landfall several times, all durations on land are added up.] The overland duration in the STI-CMA has a slowly rising trend (not significant) but changes little in JTWC. Additionally, the 101.2 hours of annual total durations of TCs with intensity exceeding 17.2 m/s in the STI-CMA dataset are longer than that of the JTWC dataset (81.6 hours). This study also calculated the average duration over land for each TC and found that it is 15.6 hours in the STI-CMA dataset and 14.0 hours in the JTWC dataset, respectively. Li et al.[17] argued that 164 TCs maintained an average of 31 hours from 1970 to 2001. Differences between the present findings and their results result from the different definitions of the overland duration because they included in their study TCs at the tropical depression strength. Therefore the calculation in this study suggests that the average overland duration is less than one day.

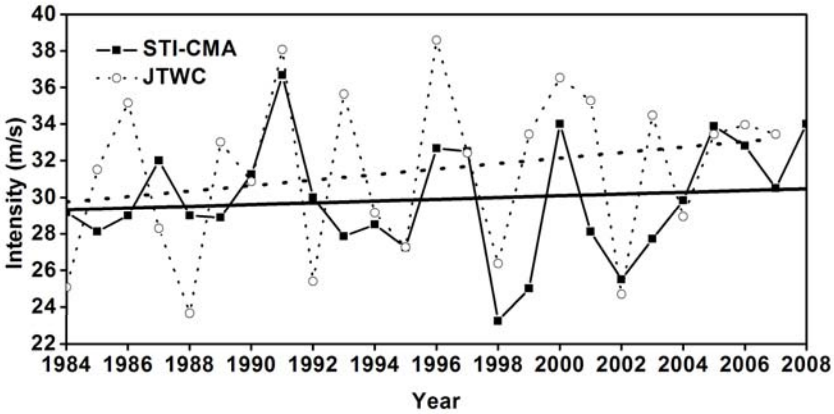

Figure 5. Annual averaged intensity for each TC at landfall based on the STI-CMA dataset from 1984-2008 and the JTWC dataset from 1984-2007 (thin curve) and the corresponding linear trend lines (thick curve), none of which passes the 95% confidence level.

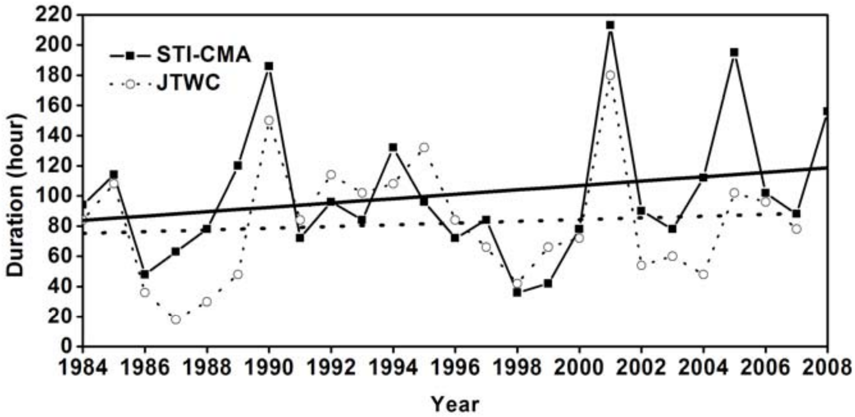

Figure 6. Total duration of TCs making landfall on a yearly basis based on the STI-CMA dataset from 1984-2008 and the JTWC dataset from 1984-2007 (thin curve) and the corresponding linear trend lines (thick curve), none of which passes the 95% confidence level.

According to Emanuel's point of view[6], the decay rate of TCs varies inversely with its intensity. That is, higher intensity leads to longer decaying time or overland duration. Table 1 shows the relationship between the landfall intensity and the overland duration of the TCs in the STI-CMA dataset (left) and the JTWC dataset (right) from 1984 to 2007. During this period, the STI-CMA dataset gets 154 samples while the JTWC dataset gets 140 samples. In Table 1, based on the landing intensity, this study divided the 154 samples from the STI-CMA dataset into four different categories (unit: m/s) and calculated the corresponding overland duration (unit: hour). Similar calculation is performed for the 140 samples in the JTWC dataset. It is clear that TCs with higher intensity may survive longer after landfall, which is in agreement with Emanuel[6].

Table 1. The intensity of TCs at landfall and the duration of the TCs after landfall based on the STI-CMA data (left) and the JTWC data (right) from 1984 to 2007.

STI-CMA			JTWC		
Intensity at landfall/(m/s)	Samples	Duration for each TC/hour	Intensity at landfall /(m/s)	Samples	Duration for each TC /hour
(15, 25]	60	11.2	(15, 30]	74	11.9
(25, 35]	72	18.0	(30, 45]	55	15.5
(35, 45]	19	17.9	(45, 60]	10	19.8
(45, 55]	3	22.0	(60, 75]	1	30.0

Although some differences exist in the two datasets in the trends of the landfall TCs, none of them is statistically significant. As shown in Figure 1, the increasing trend of direct economic losses is due to the influences of economic development. The STI-CMA dataset suggests that TC intensity and frequency do not show any significant change during the past 25 years while there is an increase of the TC overland duration. It should be pointed out that the TC destructive power (frequency, intensity and duration) does not decrease significantly but the percentage of direct economic losses of GDP and the deaths due to the TC-related disaster are decreasing in the same period (Figures 2 and 3). It shows that the TC forecast and the effort in TC-related disaster prevention has played an important role over the past 25 years.

4 ANALYSIS OF TC-RELATED DISASTERS IN THE COASTAL PROVINCES

4.1 *TC-related disasters of coastal provinces*

Figure 7 shows the direct economic losses by TCs that affected Hainan, Guangdong, Fujian and Zhejiang during 1984–2008, which have been adjusted with the GDP factor. The direct economic losses in the four provinces account for 65.8% of the total TC-related losses in China; i.e., 7.3% in Hainan, 25.0% in Guangdong, 11.5% in Fujian and 22.0% in Zhejiang. Figure 7 shows a significant downward trend in Guangdong at the 95% confidence level, an insignificant decreasing trend in Fujian and Zhejiang, but little change in Hainan. The results in Figure 7 are consistent with the trend of the total direct economic losses in China (Figure 2).

The TC-related casualties in the four provinces during 1984–2008 account for 68.1% of the total casualties in China, or 2.5%, 18.4%, 18.2% and 29.0% for Hainan, Guangdong, Fujian and Zhejiang, respectively (See Figure 8). Over the 25-year period, the death toll generally decreased with time in the four provinces although the trends are not significant at the 95% confidence level. As we know, in addition to the efforts taken by governments, TC-related casualties are also related to the characteristics of TCs that affected these provinces. Thus we will discuss changes in the frequency, intensity and duration of TCs that made landfall on the four provinces during the 25 years.

4.2 *Frequency, intensity and duration of TCs making landfall on coastal provinces*

The STI-CMA dataset is used in this section since we believe that more observations were included in the dataset for TCs that made landfall in China. Figure 9 shows the annual frequency of landfall TCs in Hainan, Guangdong, Fujian and Zhejiang during 1984–2008. That is 1.4, 3.0, 1.4 and 1.0 for the four provinces, respectively. Zhang et al.[2] examined the annual frequency of landfall TCs during the period 1983–2006 and the annual frequency is 1.3, 2.9, 1.2 and 0.9 in these provinces, respectively. It is evident that the landfall frequency in Guangdong is three times as large as that in Zhejiang. However, the difference of the direct economic losses is small between Guangdong and Zhejiang. Figure 8 also shows that that the TC-related mortality in Zhejiang is 1.6 times as large as that in Guangdong, suggesting that TCs in Southeast China can cause more damages than those in South China although Southeast China experiences fewer TCs. As shown in Figure 9, landfall frequency shows little change in Hainan, but drops with time in Guangdong, in agreement with Yang et al.[10]. In Southeast China, little change in landfall frequency is found in Fujian, while there is an increasing trend in Zhejiang, significant at the 95% confidence level. The two opposite trends in South China and Southeast China lead to little change in the trend of the total landfall TCs (Figure 4).

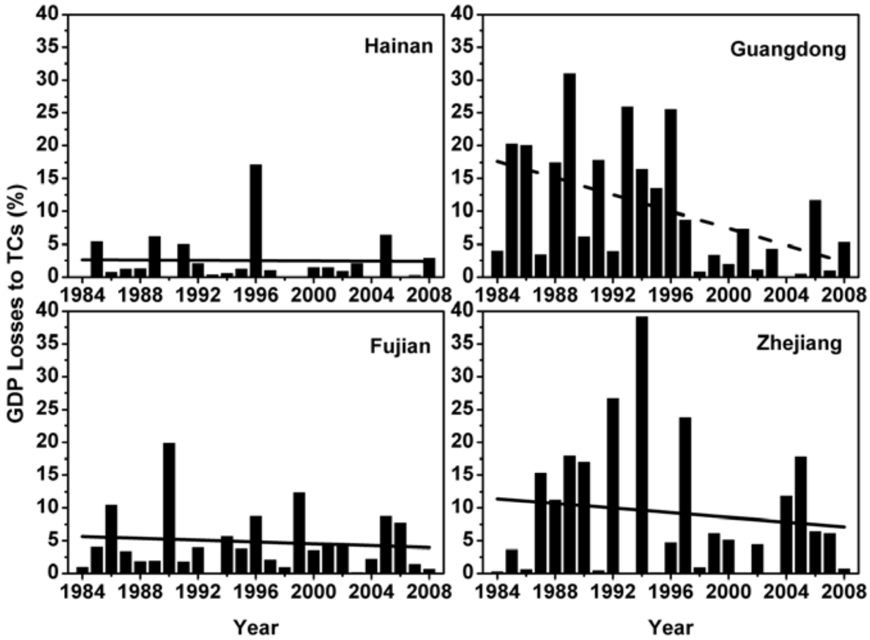

Figure 7. Direct economic losses due to TCs relative to the annual GDP in Hainan, Guangdong, Fujian and Zhejiang provinces during the period 1984-2008 (bars, unit: %) and the corresponding linear trend lines (curves). Dashed lines indicate significant trends at the 95% confidence level while solid lines indicate insignificant trends.

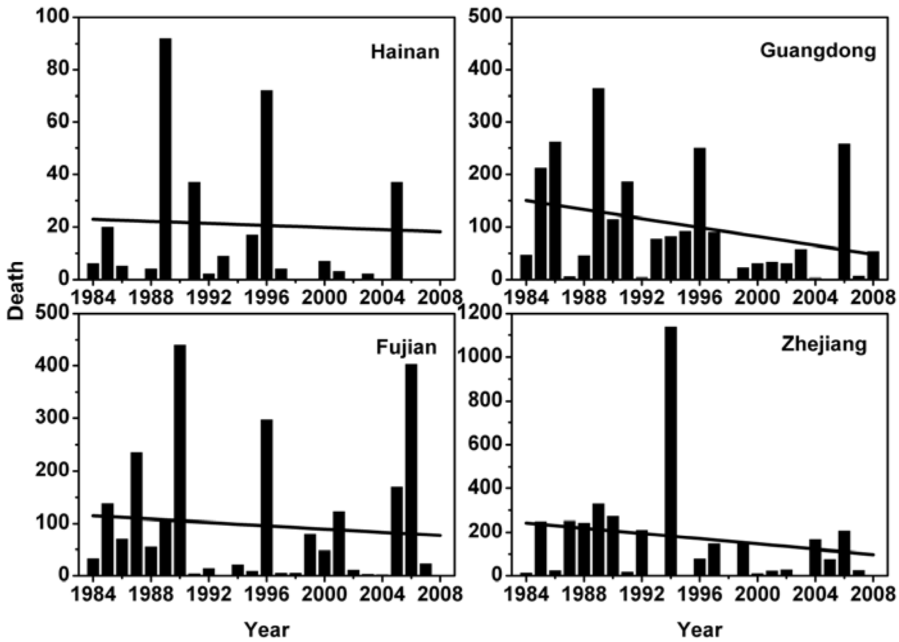

Figure 8. Same as Figure 7 but for TC-related casualties.

TC landfall intensity also plays an important role in TC-related damages. The average intensity at landfall in the four provinces is 30.8, 29.4, 29.5 and 35.0 m/s, respectively. It can be seen that the landfall intensity reaches the typhoon strength in Zhejiang despite less landfall frequency. This is why fewer landfall TCs caused more damages in Zhejiang. It is supposed that the landfall intensity is one of the most important factors to cause TC-related damages in China. As shown in Figure 10, the landfall intensity has increased in Zhejiang since 1984 with a decreasing trend in landfall intensity in Hainan. No significant trends can be found in the landfall intensity in Guangdong and Fujian. As a result, no nationwide trend is detected in the landfall intensity.

The reason for the highest landfall intensity in Zhejiang is twofold[22]. First, Among the TCs that make landfall on Guangdong and Hainan, some are formed in the South China Sea without full development before landfall. On the other hand, most of the TCs that make landfall on Zhejiang are generated over the WNP, and the long residing time over the warm ocean surface allows the TCs to fully strengthen. Second, TCs that make landfall on the south part of Fujian, Guangdong and Hainan are subjected to the influence of islands (e.g., Taiwan or Luzon), while TCs that make landfall on northern Fujian and Zhejiang take a track over the vast ocean area between Japan and Taiwan Island.

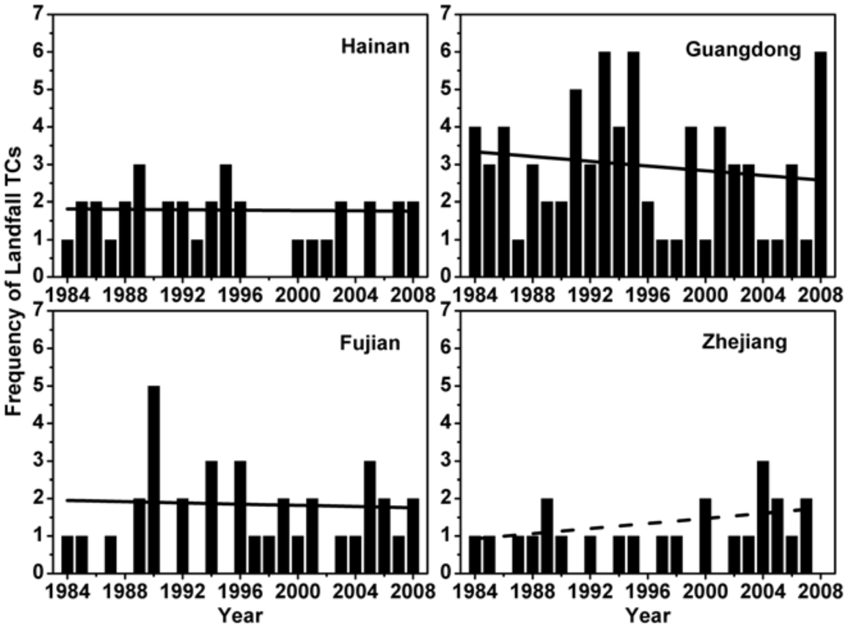

Figure 9. Same as Figure 7 but for annual frequency of TCs making landfall.

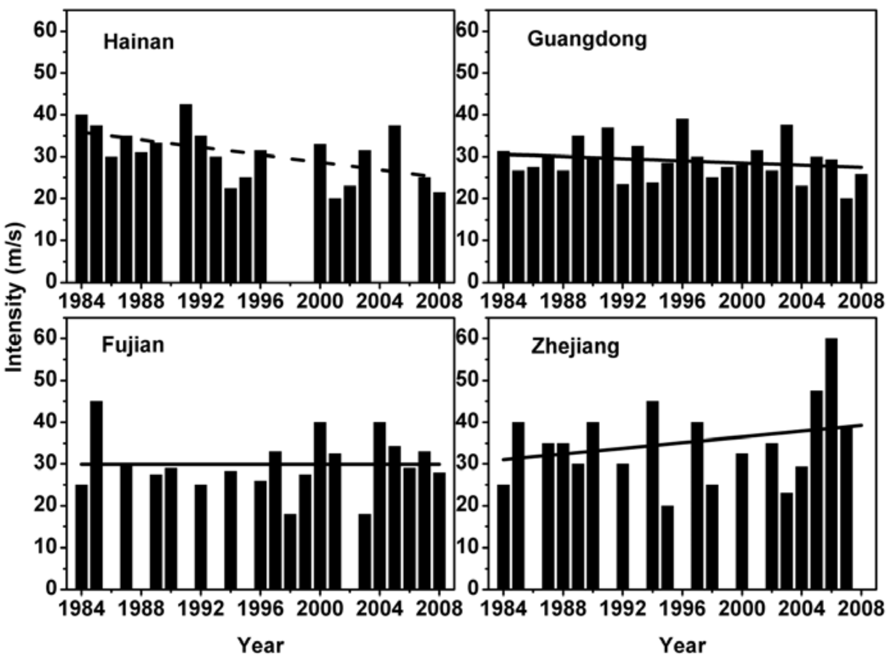

Figure 10. Same as Figure 7 but for annual averaged intensity for individual TCs at landfall.

Figure 11 shows the average TC duration in the four provinces for the period 1984–2008. The overland duration is 6.7, 6.9, 10.5, and 13.1 hours for Hainan, Guangdong, Fujian and Zhejiang, respectively. The TCs that make landfall on Fujian and Zhejiang last longer. This is one of the reasons for more serious influence of TCs on the two provinces. Figure 11 indicates that the trend of the overland duration is significant in Fujian with no significant trends in Guangdong, Hainan and Zhejiang. Note that the overland duration is calculated for individual provinces. After making landfall, TCs can affect several coastal provinces and some of them can also affect inland provinces. The increasing duration may be linked to the decreasing dissipation of landfall TCs in Fujian.

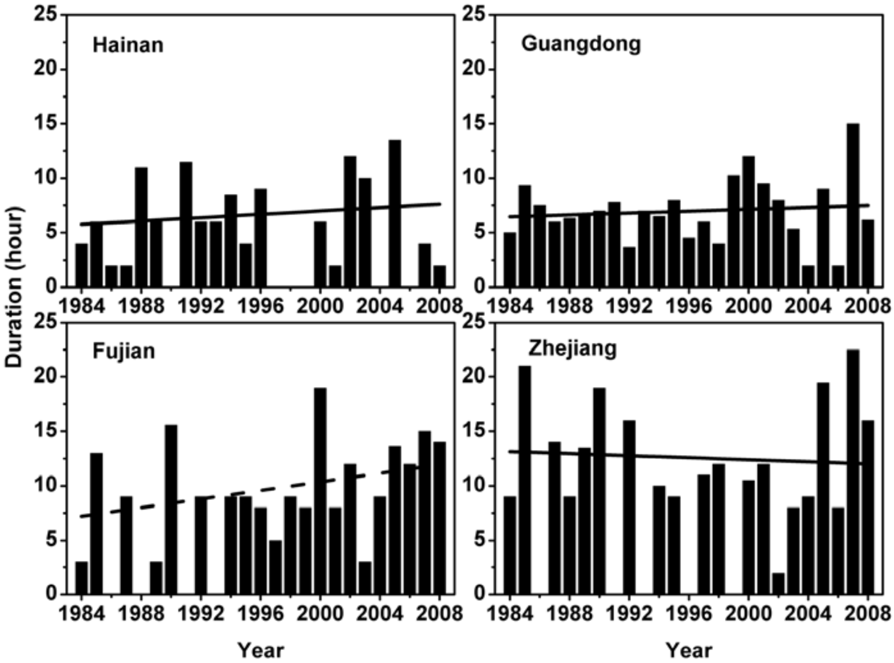

Figure 11. Same as Figure 7 but for annual averaged duration for individual landfall TCs.

In summary, over the past 25 years the changes of the direct economic losses with GDP adjustment and deaths due to TC-related disasters in the four coastal provinces are consistent with the changes in China, with a decreasing trend except for Hainan. The direct economic losses in Guangdong decreased significantly at the 95% confidence level. In terms of the characteristics of landfall TCs, landfall intensity in Hainan decreased, and the duration in Fujian increased, while the landfall frequency in Zhejiang increased. The changing trends shown here agree with Wu et al.[9] that TC prevailing tracks shifted westward over the past four decades. That is, more TCs affected Fujian and Zhejiang. The changes in the prevailing tracks may be associated with the westward extension of the subtropical high[12]. Recently, Zhou et al.[13] found that the increasing temperature in the Indian Ocean and West Pacific can lead to the westward extension of the subtropical high. On the other hand, although the duration of landing TCs has increased in Fujian and there also is an increase of TC landfall frequency in Zhejiang, the fact that the property losses and deaths have decreased implies that the effort of TC-related disaster mitigation and prevention has been effective over the recent decades.

5 CONCLUDING REMARKS

China has experienced significant economic growth over the past thirty years and the governments at all levels have paid much attention to disaster prevention and reduction. The Ministry of Civil Affairs and National Bureau of Statistics collect and release the annual TC-related disaster data, which are validated and compiled by the National Climate Center. TC activity can be affected by the ongoing global warming and may have undergone changes. To better prevent and reduce TC-related disasters, this study mainly focuses on the effectiveness of disaster management and impact of climate change on TC-related disasters in China, particularly under global warming.

Over the past 25 years, an average of 6.5 TCs makes landfall on mainland China and Hainan Island with an average intensity of 29.9 m/s and maintained the TC intensity for 15.6 hours over land. This leads to 505 deaths and 37 billion yuan (US$5.4 billion) worth of direct economic loss, which account for 0.4% of the annual GDP. Little change was observed in the overall landfall frequency, intensity and overland duration. While the annual total direct economic loss increased significantly due to the rapid economic development over the past 25 years, both the ratio of the economic loss to the GDP and the fatalities decreased, the latter of which are statistically significant at the 95% level.

Over the past 25 years, the intensity of the TCs making landfall in Hainan has decreased, while the overland duration of landfall TCs in Fujian and the frequency of landfall TCs in Zhejiang have increased, respectively. These results agree with Wu et al.[9] that TC prevailing tracks over the WNP have shifted westward, likely due to the ongoing global warming. Among the four coastal provinces, Zhejiang experiences the highest landfall intensity and longest overland duration. It is likely that Zhejiang may experience greater economic losses and fatalities under global warming. More attention should be paid to the investigation of influence of global warming on TC activity. The fact that both relative direct economic losses and fatalities have decreased at the provincial and national levels suggests that the efforts of disaster prevention and reduction that have been made over the past decades are effective, in addition to the improvement of accuracy made in TC forecast.

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